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MODELLING OF THE DURABILITY OF CONCRETE STRUCTURES

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1. Introduction

Safety and economical operation have to be ensured for a structure during its service life. This emerges the necessity for:

- Design and residual reliability level assessment;
- Design of structures for durability;
- Instruments for balancing service life vs. initial costs, maintenance and repair costs.

In this context, time is the decisive variable and the durability issues affecting concrete structures are significant. This is also clearly reflected in recent standardization activities where design for durability is dealt with: ISO 13823 [1], *fib*-Model Code [2] and ISO 16204 [3]. These documents deal with probabilistic approaches and introduce the design of structures for durability – i.e. a time-dependent limit state approach which takes service life into account. It appears that predictive models are needed to estimate how resistance (and/or loads) will change over time, and the involved uncertainties (both epistemic and eleatoric) need to be given proper consideration. Probabilistic approaches are advocated; it should be noted that the design service life is also defined by a level of reliability with regard to whether or not the relevant limit state (LS) will be exceeded during this period (based on the appropriate consequence class, combined with consideration of the cost and of safety measures). Durability and reliability issues should be addressed during the design process and discussed with the client.

The aim of the present contribution is to review the results of about 20 years of research in the area of concrete durability performed at Brno University of Technology at the Faculty of Civil Engineering's Department of Structural Mechanics and Department of Chemistry by the "Degradation" team (the members of which have gradually changed over time). This research has dealt with a broad variety of deterioration effects that attack concrete and reinforcement, and with appropriate models for use in design practice in the assessment of the required reliability level and service life of structures. Selected works published from 1993 until 2014 are listed below [4-39].

2. Durability Limit States

Reinforced concrete is a durable and widely used construction material. Despite the fact that the majority of reinforced concrete structures show good long-term performance and high durability, a large number of these structures still fail. When considering the Limit States (LS) caused by the degradation of reinforced concrete structures, four kinds of attack may be distinguished:

I. mechanical (mechanical load – static or dynamic),
II. chemical (carbonation, chloride and acid attack, alkali-aggregate reaction),
III. electrochemical (corrosion of reinforcement) and
IV. physical (freeze-thaw, abrasion, fire and others).

The present contribution focuses on cases (II) - (IV).

Limit states have been incorporated in the basic approach utilized for structural design all over the world during the last few decades. The *Ultimate Limit State* (ULS) and the *Serviceability Limit State* (SLS) are evaluated while designing/assessing a concrete structure. The general condition for the probability of failure P_f reads:

$$P_f = P(A \geq B) < P_d \tag{1}$$

where A is the action effect, B is the barrier and P_d is the design (acceptable, target) probability value. Index of reliability β is alternatively utilized in practice. Generally, both A and B (and hence P_f) are time dependent. Durability is related to the *design working life* t_D (or service life). The most generally used design method – the partial safety factor method – does not assess the reliability level directly, i.e. it does not arrive at a specified value for the relevant reliability level and is not suitable for service life assessment. This situation can be amended via utilization of the fully probabilistic approach (which is legally applicable according to current standards, but is not yet commonly accepted in practice). This approach is dealt with in the present work and is based on the LS approach in the context of durability limit states – see e.g. [23, 26, 34]. Owing to either carbonation of the concrete or the ingress of chlorides into the concrete, depassivation of reinforcing steel occurs, leading to steel corrosion. For the purposes of the durability assessment of concrete structures

a distinction is usually made between the initiation period (depassivation of the surface of reinforcement) and the propagation period of the corrosion process.

3. Degradation modelling

Modelling of degradation processes may be based on different levels of sophistication:

a) macro-level;
b) meso-level;
c) micro-level.

The *a-level* is the simplest, involving what are often called the “deemed-to-satisfy” set of rules (mostly according to current codes), and does not allow for the design/assessment of a specified service life with a specified reliability level. The *b-level* comprises simple models (often semi-empirical), which are verified by comparison with the results of testing under experimental and real conditions. The variables involved may be treated as random quantities, and therefore the outputs are also capable of expressing statistical and probabilistic characteristics with respect to their evolution over time (service life assessment). This is the level dealt with in the present work. The *c-level* is the most refined; the models used at this level are complex and are developed to make use of fundamental physical laws and often constitutive laws of mechanics, thus leading to the problem of needing to solve partial differential equations. This level of sophistication is not suitable for everyday design practice. Note that levels *b* and *c* may be viewed as performance-based design [36]. Mathematical modelling is a useful tool for the accomplishment of such a task. As several models for the degradation process in question may be available, the engineer needs to select a suitable one for each specific use. The governing criteria for such a choice are often the availability of model data and their statistical characteristics, and/or the availability of relevant testing methods, and/or the availability of effective software tools. The relevant values of variables *A* and *B* used in LS - Eq. (1), which are random quantities, have to be assessed via the utilization of a stochastic approach and a suitable degradation model. For this purpose, effective probabilistic software tools are needed. For a comparison of some models see [35]. The interrelation of safety measures, durability and costs has been dealt with in [39].

4. Software tools

As part of the presented research three software tools were developed.

(I) The FReET-D software package is a feasible and user-friendly combination of analytical models and simulation techniques. Models for carbonation, chloride ingress and reinforcement corrosion, sulphate attack on concrete in sewer collection systems, acid attack and frost attack are available. Altogether, 32 models are implemented as pre-defined dynamic-link library functions selected from the literature. The fully probabilistic safety formats are employed, serving also for the provision of quantitative information concerning a structure's safety level. The uncertainties associated with parameters involved in deterioration processes are modelled by random variables, and several simulation techniques may be optionally used (Crude Monte Carlo, Latin Hypercube Sampling or FORM). Statistical, sensitivity and reliability analysis is provided. Several features are offered, including parametric studies and Bayesian updating. Some of the models were originally developed as deterministic models and have been converted into a probabilistic form for the purposes of the presented software. Statistical correlation of input variables is efficiently imposed by a stochastic optimization technique – simulated annealing. Sensitivity analysis is based on nonparametric rank-order correlation coefficients. For more details please see www.freet.cz, [25, 37].

(II) An interactive web page, *RC LifeTime,* is freely accessible at www.freet.cz. It performs statistical and reliability analyses of concrete degradation due to carbonation [22, 30].

(III) Cellular automata were used to simulate the diffusion process as a 2D task. The proposed methodology was applied to the degradation assessment of civil engineering structures; it describes the spatial and temporal variability of harmful substance ingress (e.g. chloride ions in concrete Chloride diffusion into the concrete of the Neumarkt-Auer Bridge in Austria was simulated using cellular automata [27, 28].

5. Applications

Several applications can be found, e.g. in [10, 11, 13, 18, 21, 22, 24, 27, 32, 38]. For the sake of saving space only one example is shown here, along with a comparison of several models [35]:

Carbonation depth was analysed for an RC cooling tower utilizing four models contained in FReET-D. The tower, which has a height of 206 m, was investigated at the age of 19.1 years; the depth of carbonation was measured (using phenolphthalein tests) at 75 locations on both the internal and external surfaces. In this way, relatively reliable in situ statistical data were obtained. Table 1 presents a comparison of the analytical results with experimental data, namely the mean and COV of carbonation depth for both surfaces of the tower. The agreement is rather satisfactory for models (c) and (d).

Tab. 1 Carbonation depths in a cooling tower: comparison of analytical models with measurements from a real structure at the age of 19.1 years [35].

	External surface		Internal surface	
	Mean [mm]	COV [%]	Mean [mm]	COV [%]
Model a	10.8	48	4.4	60
Model b	8.2	24	1.9	43
Model c	12.7	18	8.3	51
Model d	11.9	21	7.7	53
On-site*	14.9	56	8.0	29

*on-site measurement (Keršner et al. 1996)

6. Conclusion

The article deals with research results obtained at the Faculty of Civil Engineering at Brno University of Technology, focusing on the service life of concrete structures, and primarily on the modelling of degradation processes. Statistical and sensitivity methods were applied to degradation processes in connection with reliability level evaluation. Several software tools were created, FreET-D being the most significant of them, covering as many as 32 degradation models. An example of carbonation progress in a cooling tower is presented.

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MODELOVÁNÍ ŽIVOTNOSTI BETONOVÝCH KONSTRUKCÍ

Summary

Cílem tohoto příspěvku je ukázat spručně výsledky asi dvacetiletého výzkumu životnosti betonových konstrukcí, zejména modelování, která byla konána na ústavech Stavební mechaniky a Chemie stavební fakulty VUT v Brně. Byly aplikovány statistické a citlivostní metody spolu s hodnocením úrovně spolehlivosti (pravděpodobnost poruchy). Bylo vytvořeno několik softwarových nástrojů, stěžejní je FReET-D, který zahrnuje v současnosti 32 modelů pro různé druhy degradace betonu či výztuže. Je ukázána aplikace na prognózu karbonatace betonové chladící věže včetně porovnání několika modelů s in-situ měřením.